

LARGE-SCALE MERCURY CONTROL TECHNOLOGY TESTING FOR LIGNITE-FIRED UTILITIES – OXIDATION SYSTEMS FOR WET FGD

Technical Progress Report

(for the period July 1 – September 30, 2004)

Prepared for:

AAD Document Control

U.S. Department of Energy
National Energy Technology Laboratory
PO Box 10940, MS 921-107
Pittsburgh, PA 15236-0940

DOE NETL Cooperative Agreement DE-FC26-03NT41991
UND Funds 4318 and 4319
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November 2004

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DOE ACKNOWLEDGMENT

This report was prepared with the support of the U.S. Department of Energy National Energy Technology Laboratory Cooperative Agreement No. DE-FC26-03NT41991. However, any opinions, findings, conclusions, or recommendations expressed herein are those of the author(s) and do not necessarily reflect the views of DOE.

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ABSTRACT

The Energy & Environmental Research Center (EERC) is conducting a consortium-based effort directed toward resolving the mercury control issues facing the lignite industry. Specifically, the EERC team—the EERC, EPRI, URS, ADA-ES, Babcock & Wilcox, the North Dakota Industrial Commission, SaskPower, and the Mercury Task Force, which includes Basin Electric Power Cooperative, Otter Tail Power Company, Great River Energy, Texas Utilities (TXU), Montana–Dakota Utilities Co., Minnkota Power Cooperative, BNI Coal Ltd., Dakota Westmoreland Corporation, and the North American Coal Corporation—has undertaken a project to significantly and cost-effectively oxidize elemental mercury in lignite combustion gases, followed by capture in a wet scrubber. The applicability of this approach is expected to increase because of an expected demand for scrubbed systems in lignite utilities as well as subbituminous utilities in the United States and Canada. The oxidation process is proven at the pilot-scale and in short-term full-scale tests. Additional optimization is continuing on oxidation technologies, and this project focuses on monthlong full-scale testing.

The lignite industry has been proactive in advancing the understanding of and identifying control options for Hg in lignite combustion flue gases. Approximately 2 years ago, the EERC and EPRI began a series of Hg-related discussions with the Mercury Task Force as well as utilities firing Texas and Saskatchewan lignites. This project is one of three being undertaken by the consortium to perform large-scale Hg control technology testing to address the specific needs and challenges to be met in controlling Hg from lignite-fired power plants.

This project involves Hg oxidation upstream of a system equipped with an electrostatic precipitator (ESP) followed by wet flue gas desulfurization (FGD). The team involved in conducting the technical aspects of the project includes the EERC, Babcock & Wilcox, EPRI, URS, and ADA-ES. The host sites include Minnkota Power Cooperative Milton R. Young Unit 2 and TXU Monticello Unit 3. The work involves establishing Hg oxidation levels upstream of air pollution control devices (APCDs) and removal rates across existing ESP and FGD units, determining costs associated with those removal rates, investigating the possibility of the APCD acting as a multipollutant control device, quantifying the balance-of-plant impacts of the control technologies, and facilitating technology commercialization.

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LIST OF ABBREVIATIONS

APCD	air pollution control device
B&W	Babcock & Wilcox
BOP	balance of plant
CMM	continuous mercury monitor
COR	contracting officer's representative
DOE	U.S. Department of Energy
EERC	Energy & Environmental Research Center
EPA	U.S. Environmental Protection Agency
ESP	electrostatic precipitator
FF	fabric filter
FGD	flue gas desulfurization
ICR	Information Collection Request (EPA)
MRY	Milton R. Young Station
NDIC	North Dakota Industrial Commission
NETL	National Energy Technology Laboratory
OH	Ontario Hydro
QA	quality assurance
QC	quality control
ROM	run of mine
SCA	specific collection area
SDA	spray dryer absorbers
SCEM	semicontinuous emission monitor
TXU	Texas Utilities

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EXECUTIVE SUMMARY

The Energy & Environmental Research Center (EERC) is conducting a consortium-based effort directed toward resolving the mercury control issues facing the lignite industry. Specifically, the EERC team—the EERC, EPRI, URS, ADA-ES, Babcock & Wilcox, the North Dakota Industrial Commission, SaskPower, and the Mercury Task Force, which includes Basin Electric Power Cooperative, Otter Tail Power Company, Great River Energy, Texas Utilities (TXU), Montana–Dakota Utilities Co., Minnkota Power Cooperative, BNI Coal Ltd., Dakota Westmoreland Corporation, and the North American Coal Corporation—has undertaken a project to significantly and cost-effectively oxidize elemental mercury in lignite combustion gases, followed by capture in a wet scrubber. The applicability of this approach is expected to increase because of an expected demand for scrubbed systems in lignite utilities as well as subbituminous utilities in the United States and Canada. The oxidation process is proven at the pilot scale and in short-term full-scale tests. Additional optimization is continuing on oxidation technologies, and this project focuses on monthlong full-scale testing.

The lignite industry has been proactive in advancing the understanding of and identifying control options for Hg in lignite combustion flue gases. Approximately 2 years ago, the EERC and EPRI began a series of Hg-related discussions with the North Dakota Mercury Task Force as well as utilities firing Texas and Saskatchewan lignites. This project is one of three being undertaken by the consortium to perform large-scale Hg control technology testing to address the specific needs and challenges to be met in controlling Hg from lignite-fired power plants.

This project involves Hg oxidation upstream of a system equipped with an electrostatic precipitator (ESP) followed by wet flue gas desulfurization (FGD). The project team involved in conducting the technical aspects of the project includes the EERC, Babcock & Wilcox, EPRI, URS, and ADA-ES. The host sites include Minnkota Power Cooperative Milton R. Young (MRY) Unit 2 and TXU Monticello Unit 3. The work involves establishing Hg oxidation levels upstream of air pollution control devices (APCDs) and removal rates across existing ESP and FGD units, determining costs associated with those removal rates, investigating the possibility of the APCD acting as a multipollutant control device, quantifying the balance-of-plant impacts of the control technologies, and facilitating technology commercialization.

While the testing phase of this effort is roughly 3 months out in schedule, there are near-term needs for preliminary planning, design, and fabrication of additive equipment and drafting of site-specific test plans. In the previous reporting period, the MRY site visit took place, and planning for additive injection began. In the current reporting period, a site-specific test plan was developed that details the efforts to be conducted. A meeting on-site was conducted with MRY plant personnel to discuss the detailed test plan. The test plan was made available to plant personnel and project sponsors for their review and comments. Test preparations will continue in the next quarter, and review comments will be incorporated into the test plan.

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1.0 INTRODUCTION

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The other projects cover sorbent injection technologies for systems equipped with ESPs and those equipped with spray dryer absorbers combined with fabric filters (SDA–FF) and an alternative oxidation technology. The overall intent of the proposed testing is to help maintain the viability of lignite-fired energy production by providing utilities with lower-cost options for meeting future Hg regulations.

2.0 BACKGROUND

Mercury is an immediate concern for the U.S. electric power industry because of the U.S. Environmental Protection Agency (EPA) December 2000 decision that regulation of Hg from coal-fired electric utility steam-generating units is appropriate and necessary under Section 112 of the Clean Air Act (1). EPA determined that Hg emissions from power plants pose significant hazards to public health and must be reduced. The EPA *Mercury Study Report to Congress* (1997) (2) and the *Utility Hazardous Air Pollutant Report to Congress* (1998) (3) both identified coal-fired boilers as the largest single category of atmospheric Hg emissions in the United States, accounting for about one-third of the total anthropogenic emissions. On December 15, 2003, EPA published the proposed Utility Mercury Reductions Rule in order to solicit comments on multiple approaches for mercury emission control. EPA is currently reviewing comments on the proposed rule and is scheduled to put forth regulations in March 2005.

Despite the fact that Hg regulations for coal-fired utilities are imminent, significant issues remain and need to be resolved. The U.S. Department of Energy National Energy Technology Laboratory (DOE NETL) has acknowledged that data gaps exist for Hg control technologies for the immense U.S. reserves of lignite and subbituminous coals. The primary challenge is that these coals produce flue gases where difficult-to-control Hg^0 is the dominant form. The EPA information collection request (ICR) indicates questions still exist regarding the impact of various APCDs and technologies for lignite-fired units on their ability to control Hg^0 emissions. The lignite-based consortium believes there is a critical need for large-scale Hg oxidation testing at lignite-fired power plants equipped with an ESP and wet FGD. This project has been developed based on the input of consortium members and DOE guidance to address these issues.

In general, lignitic coals are unique because of highly variable ash content, ash that is rich in alkali and alkaline-earth elements, high oxygen levels, high moisture levels, and low chlorine content. Lignite coals typically contain comparable levels of Hg but significantly lower levels of chlorine compared to bituminous coals. Lignites have chlorine concentrations well below 200 ppm in the coal, whereas Appalachian and Illinois Basin bituminous coals can have chlorine levels in excess of 1000 ppm. These differences in composition have been shown to have important effects on the form of Hg emitted from a boiler and the capabilities of different control technologies to remove Hg from flue gas. Coals containing chlorine levels greater than 200 ppm typically produce flue gas dominated by more easily removable mercuric compounds (Hg^{2+}), most likely mercuric chloride (HgCl_2). Conversely, experimental results indicate that low-chlorine (<50 ppm) coal combustion flue gases (typical of lignite) contain predominantly Hg^0 , which is substantially more difficult to remove than Hg^{2+} (3). Additionally, the generally high alkali and alkaline-earth contents of lignite coals may reduce the oxidizing effect of the already-low chlorine content by reactively scavenging chlorine species (Cl , HCl , and Cl_2) from the combustion flue gas. The level of chlorine in flue gases of recently tested lignites from North Dakota and Saskatchewan ranged from 2.6 to 3.4 ppmv, with chlorine contents ranging from 11 to 18 ppmw in the coal on a dry basis, respectively.

Very little published data exist demonstrating the effectiveness of oxidation technologies for plants firing lignite coal. Lignite-fired power plants have shown a limited ability to control Hg emissions in currently installed ESPs, SDAs, and wet FGD systems (4). This low level of

control can be attributed to the high proportions of Hg^0 present in the flue gas. Typically, the form of Hg in the pulverized and cyclone-fired units is dominated by the Hg^0 content being greater than 85% of the total, and the average emitted from North Dakota lignite-fired power plants is roughly 6.3 lb/TBtu (4, 5). Figure 1 shows resulting Hg emissions measured using the Ontario Hydro (OH) method and continuous mercury monitors (CMMs) for Hg at the furnace exit during pilot tests at the EERC with North Dakota lignite. These results are consistent with the ICR results discussed above and with the recent baseline data for the proposed test sites, as shown later.

Hg oxidation technologies being investigated for lignites include catalysts and chemical agents. The catalysts that have been tested include selective catalytic reduction catalysts for NO_x reduction, noble metal-impregnated catalysts, and oxide-impregnated catalysts. The chemical agents include chlorine-containing salts and cofiring fuels that contain oxidizing agents (6, 7).

Theoretically, the use of chloride compounds to oxidize Hg^0 to Hg^{2+} makes sense. The evidence includes chemical kinetic modeling of bench-scale test results, indicating that the introduction of chloride compounds into the high-temperature furnace region will likely result in the production of atomic chlorine and/or molecular chlorine, which are generally thought to be the dominant Hg^0 reactants in coal combustion flue gases (6). The formation of atomic chlorine is a key pathway involved in the chemical reaction mechanisms that result in the oxidation of Hg^0 (6). The pathway for Hg oxidation is by gas-phase Hg^0 oxidation by atomic chlorine (chlorine radical). Recent kinetic modeling of chlorine radical formation as a function of

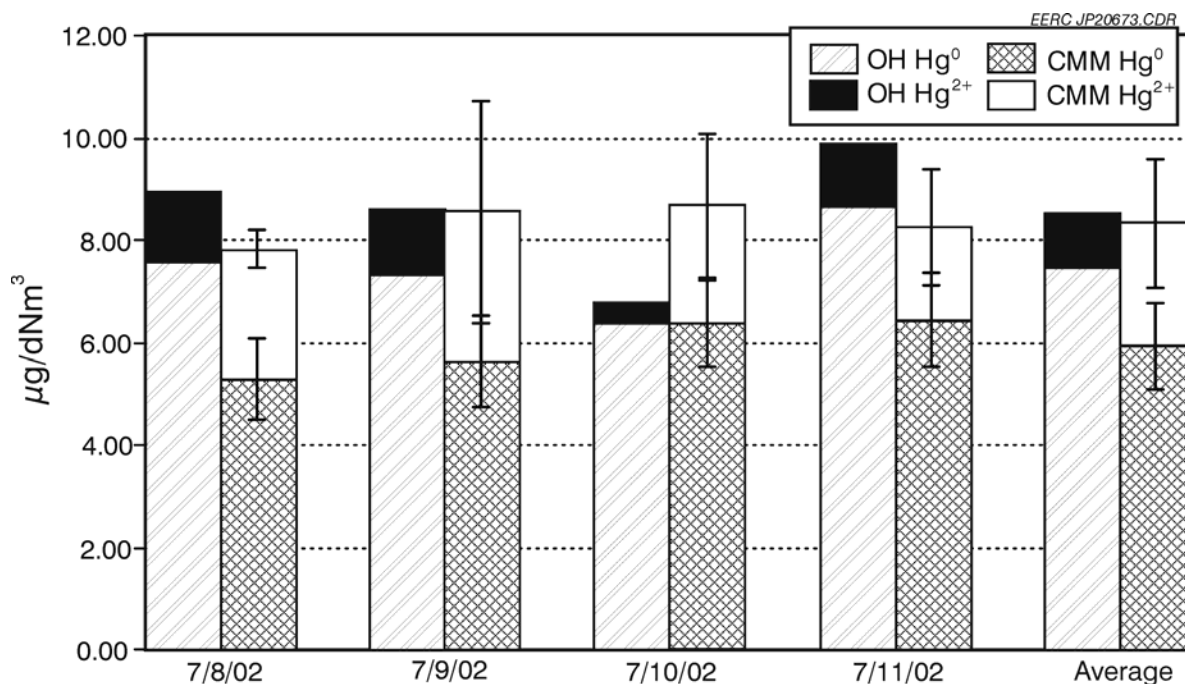


Figure 1. Inlet mercury speciation for Freedom, North Dakota, lignite ($\mu\text{g}/\text{dNm}^3$ = microgram per dry normal cubic meter [corrected to 0°C and 3% O_2]).

temperature and residence time is shown in Figure 2. The results indicate the importance of temperature in the abundance of chlorine radicals. Recent work, supported by EPRI, indicated that injection of HCl in lower-temperature regions downstream of the boiler was ineffective in oxidizing Hg^0 while injection of salt into the furnace resulted in significant oxidation (8).

Fuel additives for Hg oxidation have recently been tested in a pilot-scale system. Chemical additives or oxidants such as chloride salts have shown the ability to convert Hg^0 to more reactive oxidized forms, as shown in Figure 3. In addition, recent EPRI short-term testing conducted at a 70-MW_e pulverized-coal-fired North Dakota power plant indicated the injection of chloride salts can result in increased Hg oxidation in the flue gas (8). Hg oxidation of up to 70% was observed at a salt injection rate that resulted in an HCl concentration of 110 ppm in the flue gas, as shown in Figure 4. In addition, the injection of salt resulted in enhanced removal of Hg across the SDA–FF, with removal efficiencies of up to 50% in short-term field testing (8).

Because of the promise seen in oxidation of Hg in flue gases produced from lignite coals, the project team is conducting long-term field testing of Hg oxidation and removal using a wet FGD at the Minnkota Power Cooperative MRY Station Unit 2 near Center, North Dakota, and the TXU Monticello Station Unit 3 near Mt. Pleasant, Texas.

MRY Unit 2 is a B&W Carolina-type radiant boiler designed to burn high-moisture, high-slugging/fouling North Dakota lignite. Nominally rated at 3,050,000 lb/hr, this unit is a cyclone-fired, balanced-draft, pump-assisted circulation boiler. The unit began commercial operation in May 1977 and is base-loaded at 450 MW gross. The unit is equipped with a cold-side ESP for particulate control and a wet FGD unit for SO_2 control. The cold-side ESP has a

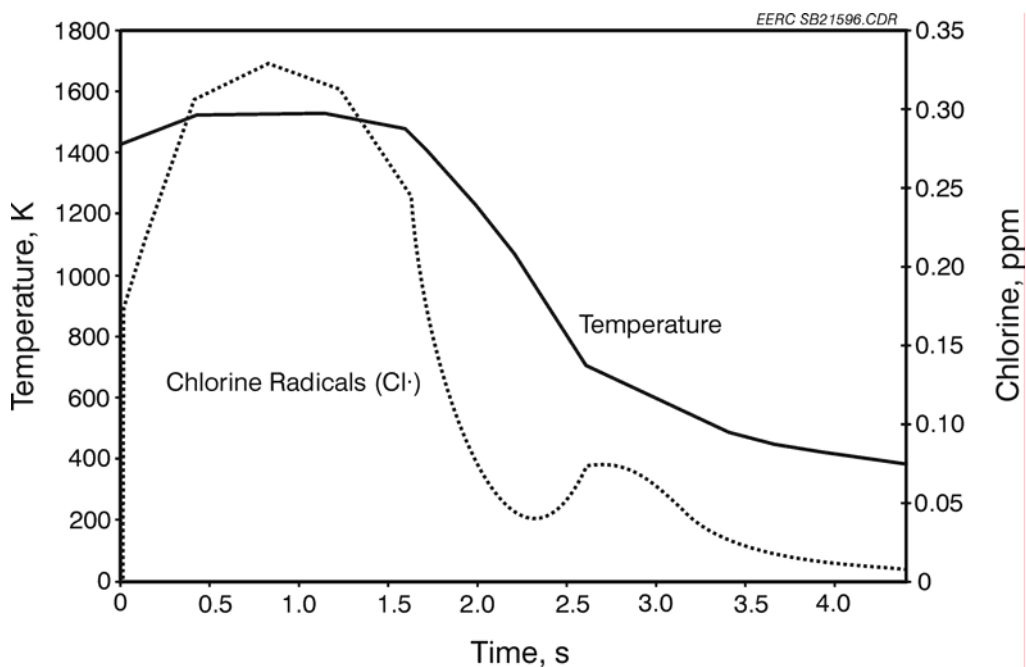


Figure 2. Prediction of chlorine radical formation as a function of temperature and residence time typical of a utility boiler using a kinetic mode (Chemkin).

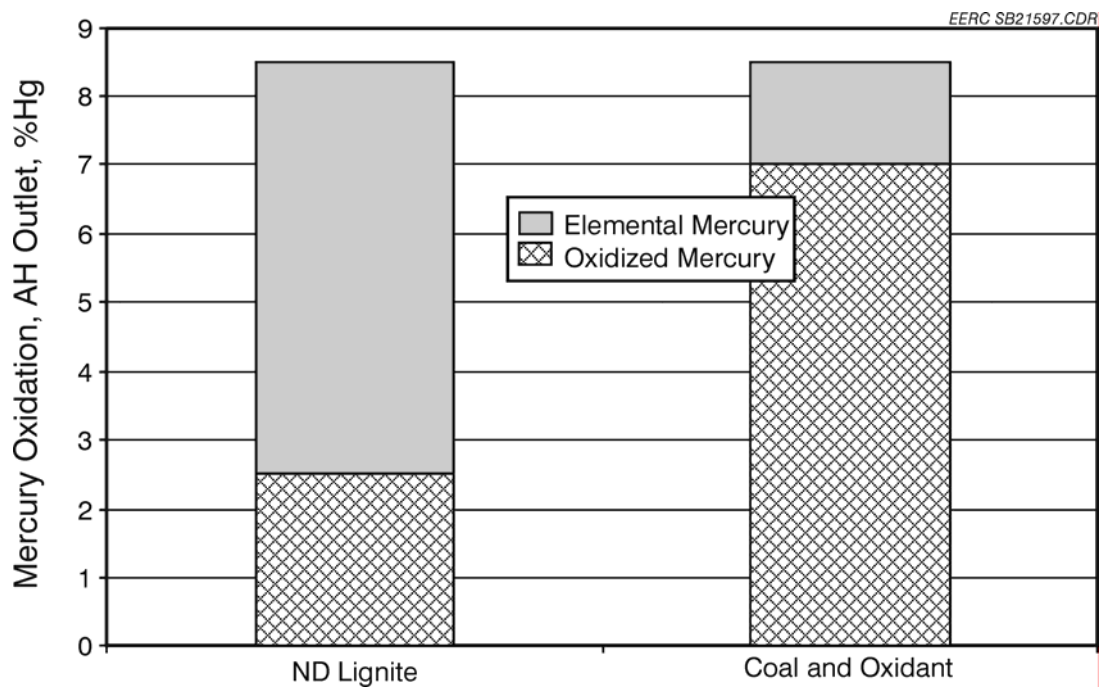


Figure 3. Oxidation of mercury through the addition of a chlorine-containing additive to the coal in EERC pilot-scale testing.

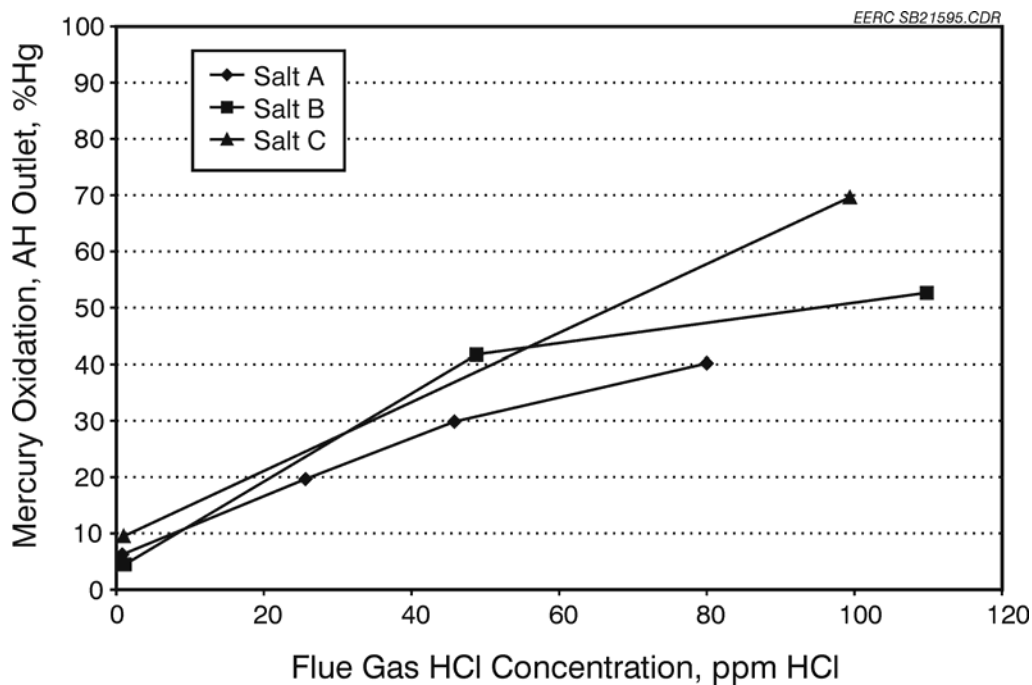


Figure 4. Comparison of mercury oxidation and HCl flue gas content for a range of salt injections at a North Dakota lignite-fired power plant (8).

specific collection area (SCA) of 375 ft²/1000 acfm. The wet FGD for SO₂ control utilizes alkaline ash and lime. The MRY Station fires North Dakota lignite coal from the Kinneman Creek and Hagel seams at the Center Mine. This plant and configuration is ideal for testing Hg oxidation and Hg control in a wet scrubber. The high-temperature environment in the cyclone will easily vaporize and transform the chlorine species into highly reactive radical forms. The system has been tested for Hg speciation and control.

Recently, flue gas sampling for speciated Hg was conducted on Unit 2 at the ESP inlet, FGD inlet, and stack from October 22 through November 14, 2002. The sampling was carried out using both the OH method and CMMs (9). A schematic diagram of the plant configuration and sample locations is provided in Figure 5. The sampling involved OH sampling at the ESP inlet, FGD inlet, and stack. In addition to OH sampling, two CMMs, one at the FGD inlet and one at the stack, were used to monitor speciated Hg levels. The CMMs were operated to obtain 20 days of data at the two locations.

The average Hg speciation results from Unit 2 OH flue gas sampling are summarized in Figure 6A. The average Hg emissions at the stack were 95% Hg⁰. Two CMMs were operated at the FGD inlet and stack locations of Unit 2 to gather Hg variability data. Statistical analysis of the CMM data indicates that the average Hg concentration was $10.7 \pm 2.7 \mu\text{g}/\text{m}^3$ (90th percentile) at the FGD inlet and $9.3 \pm 2.2 \mu\text{g}/\text{m}^3$ at the stack. Hg-level fluctuations due to minor coal changes as well as other variability in plant operations were found to fall within 24% of the average. A Hg balance for MRY Unit 2 (10) was determined by comparing the rate of Hg entering the plant to the rate of Hg leaving the plant. The resulting material balances ranged from 102% to 103%.

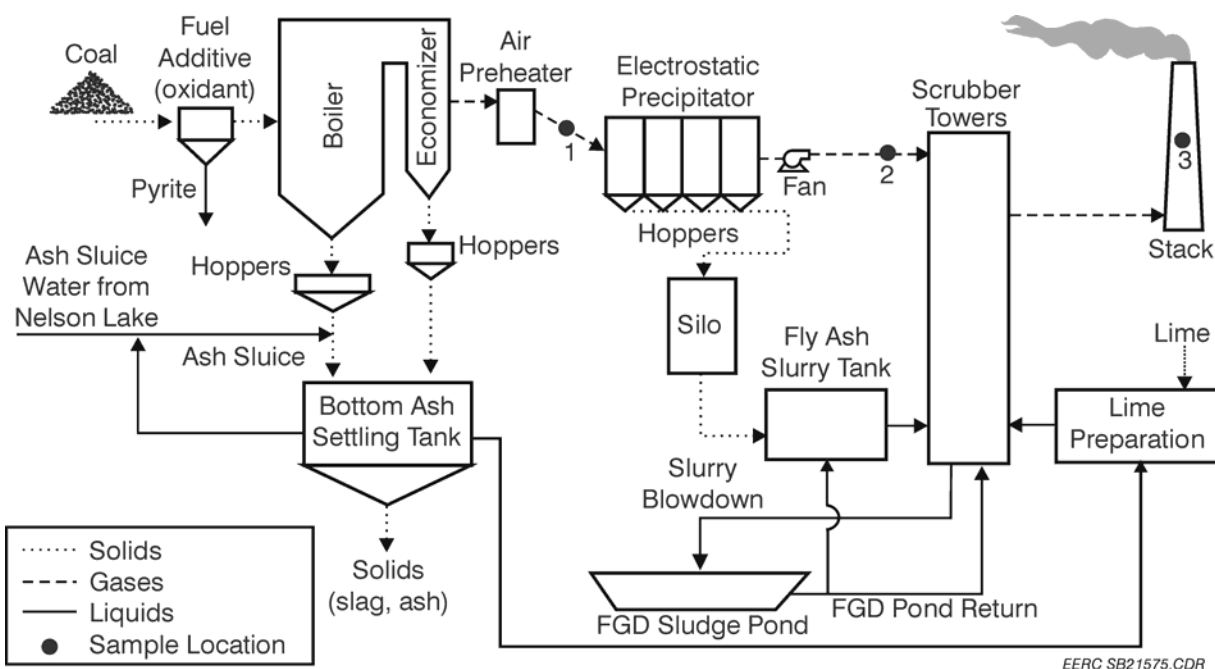


Figure 5. Schematic for MRY Station Unit 2 showing sampling locations.

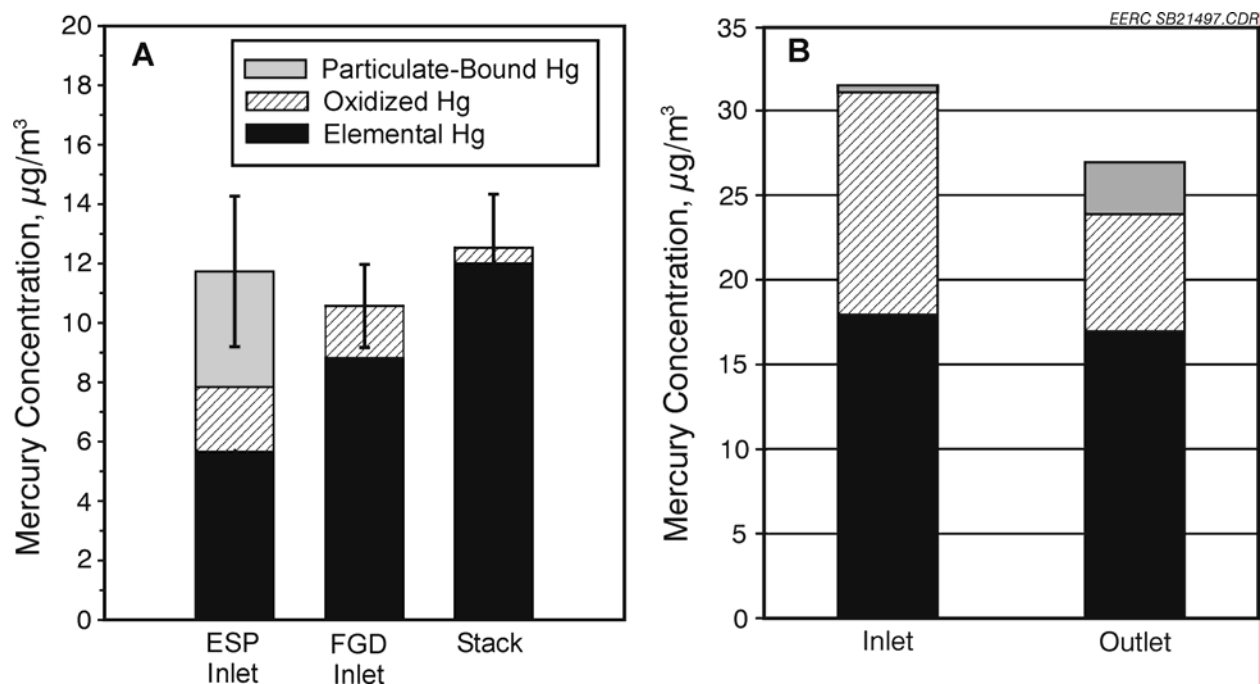


Figure 6. A) MRY OH mercury data obtained in October/November 2002 and B) OH mercury data for Monticello (ICR data).

The second site is the Monticello Unit 3 power plant located near Mt. Pleasant, Texas. This site is also well characterized for Hg speciation, emissions, and variability. In addition, it provides an opportunity to test the Hg oxidation technology on a Texas lignite. Figure 7 illustrates the Unit 3 gas path. Unit 3 has a 750-MW B&W opposed-fired, Carolina-type universal pressure boiler that fires Texas lignite coal from the upper and lower Wilcox seam. The unit was placed in commercial operation in 1978 and fires 640 tons/hr of Texas lignite at full-rated load. Downstream of the air preheater, the gas flows through a cold-side ESP constructed by Hamon Research-Cottrell. The ESP has ten fields with an SCA of 900 ft²/1000 acfm. The ESP outlet temperature is nominally 300°F.

The results of Hg speciation measurements at the inlet and outlet of the scrubbers at the Monticello Unit 3 plant are shown in Figure 6B. The results of the OH method indicate that 57% of the total Hg is in the elemental form entering the wet FGD and that the Hg⁰ is not captured with the wet FGD. Results from the ICR tests at Monticello Unit 3 suggest approximately 15% Hg removal across the FGD system, which is consistent with the trends for other units firing low-rank lignite coals.

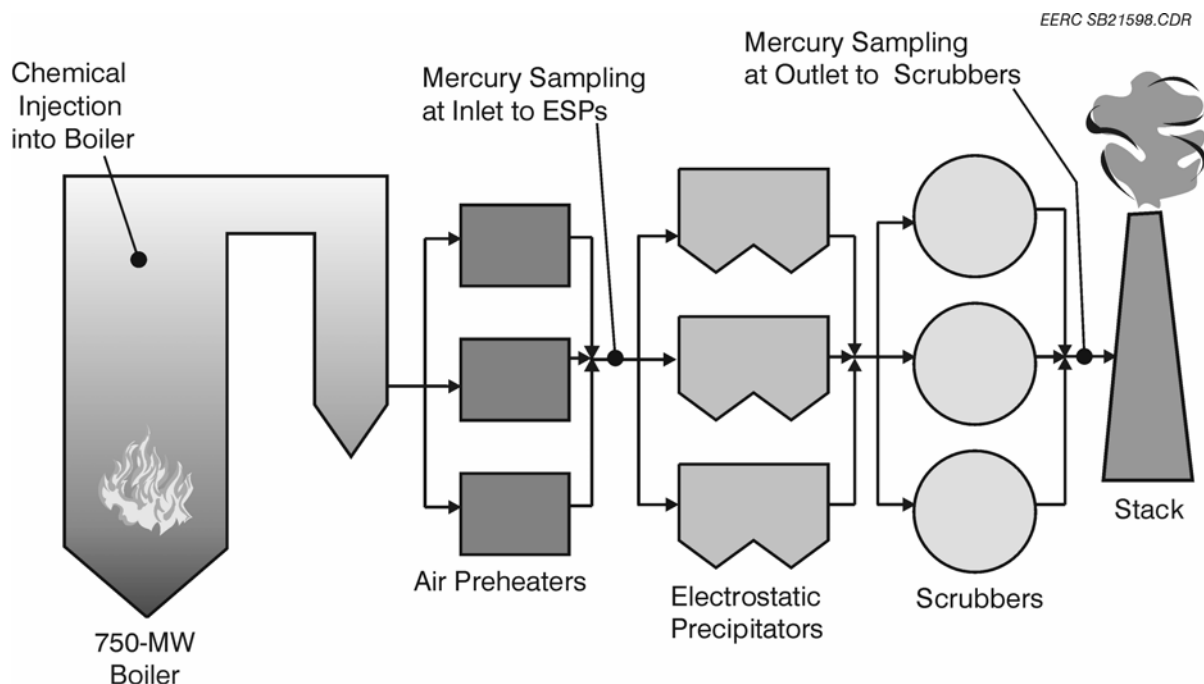


Figure 7. Plant schematic for Monticello Unit 3.

3.0 EXPERIMENTAL

3.1 Objectives

The objective of this project is to demonstrate the effectiveness of chemical addition for reducing Hg emission from flue gas derived from lignite. Full-scale tests will be performed at Minnkota Power Cooperative's MRY Station Unit 2 and TXU's Monticello Station Unit 3 to evaluate chemical addition performance across an ESP wet scrubber configuration.

The objective of the MRY Unit 2 testing is to determine the impact of chemical addition on Hg speciation, overall Hg removal from the flue gas using the combination of the ESP and wet scrubber, and the impact of the chlorine-containing salt on corrosion and deposition on system components. The objective of the Monticello testing is to provide additional data on Hg oxidation and removal efficiency when a lignite coal from Texas is fired. Data from this program will be used to perform an economic analysis of the costs associated with full-scale implementation of a chemical addition system.

3.2 Planned Scope of Work

The scope of work is aimed at testing Hg oxidation technology for controlling Hg emissions at two lignite-fired power plants equipped with wet FGD systems. The plants include the MRY Unit 2 (cyclone-fired, North Dakota lignite, ESP, wet FGD) and Monticello Unit 3 (wall-fired, Texas lignite, ESP, wet FGD). The technology involves the injection of a chemical additive with the lignite or injection into the furnace to oxidize Hg upstream of a wet FGD

system. The two plants with different firing systems and lignite types will be tested to determine the following: degree of mercury oxidation as a function of chemical addition rate, Hg removal efficiencies, economics, and BOP impacts. The additive will be added at rates equivalent to 300 to 1000 ppm chlorine in the coal during parametric testing, with a target of less than 500 ppm in the coal for the long term if selected. A second additive (SEA2) has repeatedly been shown to be even more effective than chlorine and will therefore be tested as well. In addition, small amounts of solid oxidizing additive (SOA) (activated carbon in this case) will be added (<1 lb/Macf) to further enhance oxidation. The 2-month test will be conducted using the additive that performs the best during parametric testing. If fractions of lb/Macf of carbon are shown effective in enhancing the SEA impact, it will also be considered for the 2-month test.

4.0 SPECIFIC TEST DESCRIPTION

4.1 Task 1 – Milton R. Young Testing

A 2-month test of chemical addition will be performed to enhance Hg oxidation and capture in wet FGD injection at the MRY Power Station. During testing, the impact of chemical addition on Hg speciation and overall Hg removal from the flue gas using the combination of the ESP and wet scrubber will be measured. The additive will be added to the boiler with the coal feed. The testing will be conducted on run-of-mine (ROM) lignite. All efforts will be made to obtain samples of lignite during the course of testing.

The proposed testing activities are summarized and categorized as 1) baseline, 2) parametric, and 3) extended. Baseline testing will generate Hg removal data with the existing configuration at normal operating conditions. Parametric testing will include variation of oxidant feed rates. Based on the results of the parametric testing, a 2-month test will be completed with a target Hg reduction of 55% using optimal rates established under the parametric tests.

The key objectives of the field tests include establishing values for baseline Hg speciation and removal, determining the oxidant feed rate required to achieve 70% Hg reduction, proving that 55% removal can be achieved over a 2-month-long test, quantifying Hg emission variability over a 2-month-long test, and determining impacts of oxidant on ash deposition and corrosion.

To meet these objectives and facilitate management and execution of the proposed test plan, the following two subtasks will be performed: Task 1.1 – Field Testing of Hg Oxidation and Control and Task 1.2 – Data Reduction, Reporting, and Management. A more thorough description of each subtask follows.

4.1.1 Task 1.1 – Field Testing of Hg Oxidation and Control

Subtask 1.1.1 – Test Site Planning and Preparation. Organizations directly involved in this part of the project include Minnkota, ADA-ES, B&W, and the EERC. B&W and ADA-ES have both extensive knowledge and experience with additive injection. The EERC has extensive knowledge and experience in the area of Hg testing and technology assessment, specifically related to coal-fired combustion systems.

Subtask 1.1.2 – Field Testing Activities. Field testing and sampling activities will be carried out by the EERC with additional assistance from on-site MRY personnel as needed. The oxidant feed rates will be varied independently to determine optimal rates while achieving predefined Hg reduction levels of 55% and 70% and maximum percentage reduction based on oxidant injection limits determined to be reasonable.

Tables 1 and 2 describe the proposed tests and the length of each test. Test conditions and sampling activities for the parametric testing will provide data for at least three oxidation agent injection rates in order to establish an injection rate versus removal efficiency curve. This will be followed by injecting oxidant at the 55% reduction rate and determining the impact of coal characteristics on removal efficiency. The long-term testing will be conducted at the 55% removal target, so the minimum amount of oxidizing agent will be added in order to minimize potential impacts on plant performance. The coal fired during the testing will be ROM Center lignite.

Table 1. Test Schedule for MRY Unit 2

Week	Date	Activities
1		Injection systems setup and shakedown
2		Setup and baseline sampling
3–4		Parametric testing
5–12		Long-term testing

Table 2. Detailed Parametric Test Outline for MRY Unit 2

Test	Chemical Additive	Additive Rate
Day 1	SOA only	Rate 1, 2, 3
Days 2 – 4	SEA-1	Rate 1, 2 , 3
Day 5	SEA-1	Rates 1, 2, 3 with SOA Rate A
Days 6 – 8	SEA-2	Rates 1, 2, 3
Day 9	SEA-2	Rates 1, 2, 3 with SOA Rate A
Day 10	SEA-2	Rates 1, 2, 3 with SOA Rate B
Day 11		Optimized Scrubber Performance

Up to three CMMs will be set up: at the ESP inlet, the ESP outlet, and the scrubber outlet. The CMMs will be operational during all parametric testing and the monthlong test to ascertain Hg removal efficiency and variability. OH sampling will be performed at the ESP inlet and outlet locations as well as the scrubber outlet to fulfill DOE requirements. OH sampling will be performed in triplicate to establish baseline speciation and removal data, during steady-state conditions for predefined parametric parameters, and several times throughout the 2-month-long test. Table 3 shows the test matrix for OH method sampling. The 2-month-long test will be at set oxidant feed rates targeted at a Hg removal efficiency of 50%–70%, with an overall time-averaged target of 55%, as required by DOE. It should be noted that to account for

Table 3. Ontario Hydro Method Test Matrix for MRY Unit 2

Test Condition	ESP Inlet	ESP Outlet	Stack
Baseline	3	3	3
Parametric	10	10	10
Long-Term Test			
Week 5	3	3	3
Week 8	3	3	3
Week 11	3	3	3

historical coal variability of approximately 25%, short-term targets must be set higher than 55% in order to achieve an overall average of 55% for the entire test period.

Samples of coal feed, ESP hopper ash, and scrubber blowdown will be collected as part of the MRY testing. These samples will be analyzed for total Hg and, along with the flue gas emission data, used to qualitatively evaluate the fate of Hg throughout the unit. The coal, ESP hopper ash, and scrubber sludge samples will be collected during the course of testing. The coal samples will be collected from one of the automated samplers at the feeders just ahead of the boiler. The scrubber sludge samples will be taken from one of the pumps exiting the scrubber. One coal sample, ESP (Field 1) hopper ash, and scrubber sludge will be collected each day. In addition, hopper ash samples will be collected periodically from the second, third, and fourth fields of the ESP.

The EERC will have a mobile laboratory set up on-site. The trailer is equipped to provide the setup, breakdown, and analysis of OH impinger trains on-site. All Hg OH samples (with the exception of the stack filter samples) will be prepared and analyzed on-site. This improves the overall quality assurance/quality control (QA/QC) of the project because if there are any problems with the sampling or test conditions, the sampling can be repeated while EERC personnel are on-site. Ash samples will be analyzed for Hg on-site. In addition, measurements of the flue gases will be conducted using EPA Method 26a.

Coal and ash samples will be shipped back to the EERC, where they will be prepared and analyzed. Coal samples will be analyzed for Hg, Cl, proximate, ultimate, and heating value. Ash samples will be analyzed for Resource Conservation and Recovery Act metals and undergo evaluation for leaching, volatilization, and biological availability of Hg as well as petrographic analysis.

Coal samples and process by-products will be collected and analyzed for Hg during the test program. This will include samples of ESP ash and scrubber sludge. The purpose is to make Hg material balance calculations and collect samples that will be sent to an outside contractor, as directed by NETL, for additional waste characterization testing. Specifically, three 5-gallon containers will be collected at each sampling location during baseline and 2-month tests.

Corrosion and deposition testing will take place for 2 months at the MRY Station. Carbon-based and stainless steel coupons will be tested using two EERC long-duration sampling probes. The air-cooled probes are 10 feet long with the end threaded to attach removable coupons, which

are fabricated from 1-inch-diameter Schedule 80 pipe. An associated control unit monitors the probe metal temperature and regulates the cooling air passing through the probe. Cooling air is vented from the end of the probe into the boiler. The probes will be placed in three locations in the boiler: the economizer, the air preheater, and the ESP. The steel coupons will then be submitted for scanning electron microscopy analysis.

4.1.2 Task 1.2 – Data Reduction, Reporting, and Management

This project will generate voluminous amounts of data over the parametric- and 2-month test periods. Data generated and collected will be logged carefully such that the oxidant effectiveness can be accurately assessed relative to both parametric- and 2-month Hg capture/reduction. Data generated throughout the test program will be reduced, interpreted, and summarized to determine overall conclusions related to performance and cost. Under this task, the EERC will conduct the following: 1) data generated throughout the test program will be reduced, compiled, interpreted, and summarized; 2) Hg speciation and total concentration will be calculated at each test location for each test and statistically averaged over short- and long-term tests; 3) Hg collection efficiency will be calculated based on coal inlet concentrations as well as on inlet and outlet measurements; 4) Hg levels and variability in the flue gas will be compared to the Hg content of the coal; 5) data logged by the plant will be reduced and plotted along with Hg to identify trends and relationships; 6) results will be summarized on Hg/carbon impacts on ash and suggestions provided on ash disposal and/or reuse; 7) oxidant effectiveness relative to Hg control will be calculated for short- and long-term tests (this should provide DOE and utilities with realistic performance values that can be used to guide decisions for future installations; operational issues that are identified during the test program will be documented); 8) important design and/or process parameters that appear to limit or impact Hg capture will be documented; 9) a complete unit Hg balance will be made by comparing flue gas Hg measurements made on the lignite fuel, ESP solids, and wet scrubber liquids and solids; and 10) the cost of Hg control will be estimated based on test results.

Summary reports, quarterly reports, and presentations will be issued to update the participating organizations and DOE on project status and results. Periodic review meetings, as necessary, will be held to present data and allow participants to provide feedback and direction. Specific to Task 1, the EERC will manage and coordinate all activities related to field tests at the MRY Station.

4.2 Task 2 – Monticello Testing

The object of this task is to demonstrate the effectiveness of Hg oxidation through chemical addition for reducing Hg emissions from flue gas derived from Texas lignite. Full-scale tests will be performed at TXU's Monticello Station Unit 3 to evaluate the effectiveness of chemical addition on Hg control across an ESP wet scrubber configuration. Monticello Unit 3 is configured with a cold-side ESP for particulate control and a wet scrubber for sulfur dioxide control. Flue gas Hg concentrations will be measured with and without chemical injection across the ESP wet scrubber configuration. Up to two chemicals will be chosen based upon a predetermined selection criteria and will be evaluated during the short-term parametric tests. Parametric tests will be used to determine the optimal process conditions for each material and

will be used to establish the conditions for each long-term test set to last 2 weeks. An economic analysis will be performed using the test data to assess costs for implementing a chemical addition-based system for Hg oxidation and removal for the plant configuration tested.

4.2.1 Task 2.1 – Field Testing of Mercury Oxidation and Control at Monticello

Initial project planning will include development of a test plan and QA/QC plan, project and site kickoff meetings, and finalizing host site and cost-sharing agreements. A project plan will be developed specifying all tasks to be carried out during the program. The plan will describe detailed activities and schedules for each task and will be reviewed by all team members and the host utility before being submitted to the NETL Contracting Officer's Representative (COR) for final review and comment. Work will begin after final acceptance by the COR. Included in the test plan will be a procedure for demobilization and disposal of all test equipment and expendable material following completion of the project. A QA/QC plan will be developed to ensure the integrity of all data obtained in this program. The QA/QC plan will be reviewed by all team members and by a QA representative from the prime contractor.

Following acceptance of the test plan and QA/QC plan, a kickoff meeting will be held to plan and coordinate all project activities. This meeting will be attended by representatives of each participating organization and will include finalization of a program schedule and coordination of all testing equipment and activities. Chemical selection criteria and existing test data will also be reviewed. This task will also include completing the host site agreement (e.g., security clearances, etc.) and all necessary work to finalize the cost-share agreements between the groups involved in the program.

4.2.2 Task 2.2 – Design and Fabrication of Additional Equipment

Monticello chemical addition tests will be carried out using rented equipment determined by the chemical type and physical form chosen. Solid addition will require the use of a silo to store the material and a screw feeder to deliver the material to the boiler, whereas liquid or gaseous chemicals will require different handling and delivery methods.

4.2.3 Task 2.3 – Monticello Unit 3 Tests

Subtask 2.3.1 – Site Setup. This subtask will consist of mobilization and site preparation efforts by test personnel. Mobilization will include all activities associated with procuring necessary equipment and reagents, equipment shipment to the site, chemical delivery, and general preparation for on-site testing. On-site activities will include setup of the addition and measurement equipment, workstations, and chemical storage equipment.

Equipment performance checks will include calibrating all necessary equipment, such as chemical feeders and Hg analyzers, and running routine QC checks on the equipment to ensure proper operation during testing. Procedures for the performance checks will be outlined in the QA/QC plan. Chemical feeders will be calibrated for mass delivery with each chemical.

EPRI will provide two semicontinuous emission monitors (SCEMs), at no cost to DOE, which will be operated by the project team. The SCEMs are based on the tendency for Hg^0 to form an amalgam with gold and the cold-vapor atomic absorption of Hg^0 that is thermally desorbed from the gold. The analyzer determines total Hg concentrations by reducing all of the oxidized Hg to the elemental form upstream of the gold or only Hg^0 concentrations by removing the oxidized Hg while allowing Hg^0 to pass through without being altered. The analyzers are calibrated and periodically verified with liquid- or gas-phase Hg standards. Flow rate calibration devices are used to calibrate the analyzer flow monitors.

Subtask 2.3.2 – Baseline Testing on Unit 3. Baseline test measurements will be made prior to chemical addition testing to characterize Hg speciation and removal during normal operation. Hg measurements will be carried out over a 3–4-day period using the EPRI SCEMs set up at the inlet to the Unit 3 ESP and the outlet of the wet scrubber. Plant operating data will be logged throughout this period for comparison with test results. Additional measurements will be made during baseline testing using manual sampling methods, as described below. A complete unit Hg balance will be made by comparing flue gas Hg measurements made on the lignite fuel, ESP solids, and wet scrubber liquids and solids. Lignite and flue gas chloride measurements will also be made during baseline testing. Flue gas halogen (HCl , Cl_2 , HF) measurements will be made across the ESP–wet scrubber during baseline testing using EPA Method 26A.

Subtask 2.3.3 – Short-Term Parametric Tests on Unit 3. Short-term parametric tests will be performed to determine the optimal chemical addition conditions for each material tested. Chemicals will be added at various rates directly to the boiler. Simultaneous Hg measurements will be made immediately upstream of the ESP and downstream of the wet scrubber. Tests will evaluate the effect of chemical addition rate on Hg speciation leaving the boiler and flue gas Hg removal across the ESP wet scrubber combination. The tests will also be used to both optimize the injection rate for each chemical and ensure that no adverse impacts occur in the plant from the chemical injection. Chemicals identified for testing at Monticello Unit 3 will be chosen based on their potential to overcome limitations demonstrated in previous injection tests in units with similar configurations.

One week of testing will be scheduled to evaluate the Hg removal effectiveness of up to two chemical additives. The specific additives to be tested will be identified from the results of full-scale testing at MRY and previous EPRI testing. To be considered for this program, each chemical will have to pass a set of criteria based on Hg oxidation and removal performance, its cost as-delivered, and its impact on fly ash.

The performance of each chemical will be evaluated at up to four injection concentrations over a 2-day period. Each injection rate will be evaluated for up to 4 hours. Following testing with each chemical, Hg measurements will continue to collect baseline Hg concentrations to ensure that baseline Hg levels are reached in the flue gas prior to beginning evaluations of the next candidate chemical. It is anticipated that up to 12 hours will be required for the flue gas Hg to subsequently stabilize between tests. The tentative chemical injection test matrix for Unit 3 is presented in Table 4.

Table 4. Proposed Monticello Unit 3 Chemical Addition Test Matrix

Test ID ¹	Chemical Setup on Unit 3	wt% Chlorine Added (% rel. to coal)	Schedule SU1–SU4 days
B1	Baseline	0	Day B1–B4
C1-a,b	Chemical 1	0.01, 0.025	Day 1 (4 hours each test)
C1-c,d	Chemical 1	0.05, 0.07	Day 2 (4 hours each test)
B-2	Baseline	0	Day 3 (24 hours)
C2-a,b	Chemical 1	TBD	Days 4–18
B-3	Baseline	0	Day 19 (8 hours)
C3-a,b	Chemical 2	0.01, 0.025	Day 20 (4 hours each test)
C3-c,d	Chemical 2	0.05, 0.07	Day 21 (4 hours each test)
B-4	Baseline	0	Day 22 (8 hours)
C4-a,b	Chemical 2	TBD	Days 23–33

¹ B = baseline, SU = setup, and C = chemical additional tests.

The planned range of injection concentrations identified for testing on Unit 3 is 0.01–0.07 wt% chlorine relative to the coal chlorine concentration. The upper end of this range should result in >90% Hg removal. The actual injection rates used will be determined by additive performance and data collected during full-scale tests at MRY and previous EPRI-funded chemical addition tests.

Plant data will be collected during the parametric tests and will include coal burn rate, boiler load, boiler oxygen, duct temperature, plant SO₂ and NO_x concentrations, and stack flow. Other plant data that will be collected periodically are flue gas HCl concentrations and flue gas moisture content. Coal samples will be collected from the plant for ultimate and proximate analyses and to analyze for Hg and chlorine content.

Subtask 2.3.4 – Extended Testing. A 10–14-day performance test will be carried out under the optimum conditions determined from the parametric tests. It is anticipated that the 10–14-day tests will begin immediately after completion of the short-term tests. The chemicals will be continuously added directly to the Unit 10 boiler at a selected addition rate. Simultaneous Hg speciation measurements will be made as described above to characterize Hg removal across the ESP–wet scrubber combination. Two SCEMs will operate continuously throughout the long-term test: one analyzer will be used at the inlet to the ESP, while the second will measure Hg at the outlet of the wet scrubber. Plant data will be collected, as described above, to determine if variations in measured Hg concentrations can be attributed to changes in system operation. The effect of chemical addition on unit operations will also be observed. Lignite samples will be collected daily and held for future Hg analysis.

Subtask 2.3.5 – Flue Gas Characterization. Flue gas characterization tests will be carried out during the first week of baseline testing to verify the SCEM Hg measurements and characterize flue gas flow rate and chloride concentration. Hg measurements will be made using the OH method (American Society for Testing and Materials D6784-02) to verify the Hg speciation measurements across the ESP and wet scrubber. Samples will be obtained simultaneously and from the same test locations as the Hg SCEM analyzers. Triplicate

simultaneous measurements will be made at the ESP inlet and wet scrubber outlet to verify both the baseline removal on Unit 3 and the SCEM operation. Measurement procedures will be carried out as defined in the sampling method and the program QA/QC plan. Samples will be shipped to URS's Austin, Texas, laboratories for analysis.

Flue gas chloride concentration will be determined using EPA Method 26a. Measurements will be made during the initial baseline period and periodically during the long-term test to characterize flue gas chloride levels exiting the boiler and subsequent removal across the ESP–wet scrubber. Method 26a measurements made during the 1–14-day tests will be done using an EPRI sampling system. Results of EPA Method 26a measurements will be used to determine chemical addition rate and, subsequently, calculate chloride loading in the flue gas.

Duct flow rate measurements will be made using EPA Method 5. Method 5 measurements will be made during each manual measurement period.

Subtask 2.3.6 – Site Report. A draft site report summarizing all activities and results obtained during testing at Monticello Unit 3 will be prepared after all testing is completed. The report will be sent to all team members, the host utility, and the prime contractor for review. After receiving comments, a final report will be prepared and sent to the COR.

4.2.4 Task 2.4 – Data Analysis

Data from the chemical addition testing at Monticello Unit 3 will be analyzed to determine Hg removal performance at each of the testing conditions. This analysis will include comparison of all results obtained from SCEM and manual measurement methods as well as all plant data to determine how the chemical addition performance corresponds to various plant operating parameters. Results of all QA checks will be used to determine the validity of the test results. Data will be analyzed during each respective test to enable determinations regarding possible operational changes to be made.

4.2.5 Task 2.5 – Waste Characterization

Process by-products will be collected during the test program for determination of Hg content and stability. The former will be performed by the project team in order to make Hg material balance calculations. This will include samples of ESP solids and wet scrubber liquid and solids. Additional samples will be collected and sent to an outside contractor, as directed by NETL, for additional waste characterization testing. Specifically, three 5-gallon containers will be collected at each sampling location during baseline and the 10–14-day tests.

4.2.6 Task 2.6 – Economic Analysis

An economic analysis will be performed at the end of the testing program to assess full-scale implementation costs for the chemical addition Hg removal systems in plants with an ESP–wet scrubber combination. This analysis will be performed using data collected during this program and will include costs categorized by chemical cost and Hg removal levels.

4.2.7 Task 2.7 – Program Management and Reporting

Program management and reporting will occur throughout the life of the project. This task includes tracking budgeting and staffing for the program, as well as creating and delivering project status reports to NETL, the prime contractor, and the host utility. Also incorporated into this task is technology transfer, preparing papers and presentations for conferences, and preparing for and attending team meetings and the NETL contractor review meetings.

5.0 RESULTS AND DISCUSSION

While the testing phase of this effort is roughly 3 months out in the schedule, there are near-term needs for preliminary planning, design, and fabrication of additive equipment and drafting of site-specific test plans. In the previous reporting period, the MRY site visit took place, and planning for additive injection began. In the current reporting period, a site-specific test plan was developed that detailed the efforts to be conducted. A meeting on-site was conducted with MRY plant personnel to discuss the detailed test plan. The test plan was made available to plant personnel and project sponsors for their review and comments. Test preparations will continue in the next quarter, and review comments will be incorporated into the test plan.

6.0 CONCLUSIONS

No data were acquired during this quarter.

7.0 REFERENCES

1. U.S. Congress. U.S. Public Law 101-549; U.S. Government Print Office: Washington, DC, 1990; 314 p.
2. U.S. Environmental Protection Agency. *Mercury Study Report to Congress*; EPA-452/R-97-003; U.S. EPA Office of Air Quality Planning and Standards, U.S. Government Printing Office: Washington, DC, Dec 1997.
3. U.S. Environmental Protection Agency. *A Study of Hazardous Air Pollutant Emissions from Electric Utility Steam Generating Units: Final Report to Congress*; EPA-453/R-98-004a; U.S. EPA Office of Air Quality Planning and Standards, U.S. Government Printing Office: Washington, DC, Feb 1998.
4. U.S. Environmental Protection Agency. *Information Collection Request*; 1999.
5. Pavlish, J.H.; Holmes, M.J. Mercury Control for Lignite-Fired Power Plants Poses a Challenge. *Center for Air Toxic Metals Newsletter* **2002**, 8 (1), 6.

6. Pavlish, J.H.; Sondreal, E.A.; Mann, M.D.; Olson, E.S.; Galbreath, K.C.; Laudal, D.L.; Benson, S.A. Status Review of Mercury Control Options for Coal-Fired Power Plants. *Fuel Process. Technol.* **2003**, 82 (2–3), 89–165.
7. Sjostrom, S.; Richardson, C.; Chang, R. *Evaluation of Mercury Emissions and Control Options for Great River Energy*; Final Report for North Dakota Industrial Commission; June 2001.
8. Chang, R.; Strohfus, M. *The Evaluation of Chemical Additives for Mercury Emission Control at Great River Energy*; Final Report for the North Dakota Industrial Commission; Jan 2003.
9. Thompson, J.S.; Holmes, M.J.; Laudal, D.L. *Long-Term Monitoring at North Dakota Power Plants*; Final Report for the North Dakota Industrial Commission; March 2003.
10. Laudal, D.L.; Pavlish, J.P.; Graves, J.; Stockdil, D. Mercury Mass Balances: A Case Study of Two North Dakota Power Plants. In *Proceedings of the AWMA Mercury in the Environment Specialty Conference*; AWMA VIP91, 1999; pp 340–34.